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A Comprehension-Based Analysis of AutoFlight System Interfaces

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Billings (1996) and other researchers (e.g., Vakil, Hansman, Midkiff, & Vaneck, 1995) have concluded that pilot models of flight automation systems are incomplete and that these models cause operation and training problems (e.g., Mangold & Eldredge, 1995). Sherry and Polson (in preparation) describe a complete model of the avionics. This report summarizes that model and its application to the design of new forms of training and flight mode annunciation.

A new design for a flight mode annunciator(FMA) will be evaluated using experimental and model based methods. The experiment is described in a proposal by McCrobie and Sherry (1996). The model based evaluation will employ a comprehension-based theory of action planning (Kitajima & Polson, 1995). The theory provides a detailed description of how information in displays and other external sources support skilled performance and of how time compression and high work load can cause errors by skilled pilots.

This report describes the model that is the foundation for the design of the new FMA. This document is a summary of Sherry and Polson (1995) and another paper in preparation.

1. The Cockpit Systems Framework

The Cockpit System Framework (Sherry, 1994; Sherry & Polson, in preparation) integrates models of the avionics (e.g., McRuer, Ashkenas, and Graham, 1973; Sherry, 1994), models of pilots (e.g., Polson, Irving, and Irving, 1993), and of the mission of safely flying an aircraft from origin to destination. The framework decomposes performance of the mission into four asynchronous tasks: flight planning, navigation, guidance, and control. The functions of the avionics are decomposed into the same tasks. This report describes the models of the automation that perform each of the four tasks.

A new, symbolic, rule-based, modeling framework, the operation procedure model (Sherry, 1994), is introduced to describe the operationally embedded flight planning, navigation, and guidance functions of the avionics. The control function of the avionics is modeled as a linear system with feedback terms (McRuer et al, 1973). The models of pilots for each tasks focus on the management of the avionics. We assume that the crew has delegated the responsibility of flying the aircraft to the avionics. Their role in the safe conduct of the mission is to make flight plan modifications as required by ATC clearances and weather and to monitor the performance of the avionics.

1.1 The Cockpit System

The Cockpit System is realized by two pilots (a Captain and First Officer), the avionics, and a user-interface for communication between the pilots and the avionics. Both Hutchins (1995) and Billings (1996) take the cockpit as the unit of analysis. The key issue in the analysis of a system with three agents is the distribution of responsibility and authority for performing the various tasks required to complete the mission. The Cockpit Systems Framework incorporates models of both the avionics and the human pilots "because it is the *interactions* among these system elements that results in the success of failure of the mission" (Billings, 1996, p. 1). The interactions between the avionics and the crew are determined by an agent's ability to communicate intentions and to comprehend and anticipate the behavior of other agents in the system.

1.2 Models of the Automation

The Cockpit System Framework assumes that successful interactions between pilots and automation are mediated by common models comprehensible to *both* designers and pilots. Modern flight automation is based on a large number of models of various components of the mission. These models include models of the atmosphere and winds, of the aircraft, and of engine performance, as well as models used to compute fuel consumption and arrival time predictions.

1.2.1 Closed-Loop Control Systems

Many of these models are key elements of closed-loop control systems. For example, the automated control task is closed-loop control systems based on models of the aircraft, the response of the aircraft to control inputs (changes in aircraft surfaces and engine thrust), the response of aircraft to external disturbances implemented as linear differential equations with feedback terms (McRuer et al, 1973). These models are continuous systems; that is, small changes in an input generate small changes in an output. Valik et al. (1995) concluded on the basis of interviews that pilots have an approximate version of these models that enable them to anticipate the behavior of the aircraft when they have delegated the control task to the automation.

1.2.2 Rule-Based Systems

Flight planning, guidance, and navigation are beyond the scope of the linear system formalisms of classical control theory (McRuer et al, 1973). The software that performs these tasks is dominated by decision-making logic (IF THEN/ELSE and CASE statements). These tasks are integral parts of the overall operation of the mission and embody the strategies and the tactics for controlling the aircraft throughout the mission. The knowledge required to make these decisions includes airspace regulations, airline policies, performance limits of the aircraft, passenger comfort considerations, and information about the weather.

A rule-based system is a symbolic system. Each rule is composed of a situation and behaviors. If the situation description in a rule matches the current situation, the rule fires and executes its behaviors. Small changes in representation can generate large changes in behavior. Such systems can be difficult to comprehend.

The early generations of the software for the flight planning, guidance, and navigation tasks have a few hundred rules for each task. The rule sets evolved incrementally as operators and developers identified performance deficiencies with early versions of the software and gained a better understanding of the separate tasks. There were no explicit methodologies for constructing the rule sets and no models for analyzing their behavior. Pilots were not provided with training about the rules; it is doubtful that such training would be useful because the rules were not designed to be comprehensible to pilots. A specific rule may or may not perform a meaningful component of a task like flightplanning or guidance.

1.3 Operational Procedure Model

The operational procedural model (Sherry, 1994) is a methodology for the design and verification of rule-base systems like those that implement the flight planning, guidance, and navigation tasks. Operational procedures decompose the computations involved in performing a task like guidance into a set of subtasks that are meaningful to pilots. Their behavior is directly determined by their current representation of the mission, which is a detailed representation of the task being performed by the system; that is, the procedures are operationally embedded. These tasks are continuously evaluating their mission representations and changing their behavior as the representation changes (i.e., they are reactive).

Operational procedures are based on pilots' representations of the tasks involved in performing the mission. This requirement is a powerful constraint on the content and structure of rules that implement the automation for each of the tasks and their subtasks.

The following paragraphs are a summary of Sherry and Polson (1995).

1.3.1 Basic Definitions

Each operational procedure is defined by a set of *scenarios* and a *behavior*, which are analogous to the situation and behavior of a rule. One or more scenarios are associated with a behavior. The scenarios are defined by a set of conditions or situations in the mission when the operational procedure should be performed.

Objective and Strategy: Each operational procedure is characterized in terms of its objective and strategy. This description must be comprehensible to pilots. The objectives and strategy of the operational procedure represent the goals of the specific maneuver that can be achieved by this operational procedure and its manner of operation. Each operational procedure is defined by a different combination of objectives and strategies.

Scenario: The scenario identifies the situation in the mission when the operational procedure shall be invoked. The scenario must define a meaningful component of the mission in terms of the task (e.g., flight planning, control) and the mission phase (e.g., preflight, cruise, or descent). The scenario takes into account the objective of the task and the current phase. For example, the scenario for a guidance operational procedure with the objective of climbing to cruise altitude takes into account the position of the aircraft relative to the flight plan, pilot selected speed and altitude restrictions, operational limits of the aircraft, and the status of the equipment.

Behavior: The behavior of each operational procedure, summarized by its objective, is a description of the actions executed by the procedure. These actions depend on the task or subtask performed by the procedure. The behaviors are the outputs of a task. For example, guidance operational procedures output to the control task a mode and a set of targets that must be maintained or acquired by the aircraft to satisfy the objectives of the operational procedure.

Flight planning, navigation, and guidance tasks have a common control structure. It is a task or data acquisition loop with inputs from other tasks and representations of the past operational procedures and scenarios (states) and possible future operational procedures and scenarios (states) of the task. Each possible pattern of inputs defines a scenario. One or more scenarios are associated with an operational procedure specifying its conditions for invocation. The code for each task is a complex case statement that is enclosed in the task acquisition loop.

The key assumption of the operational procedure model is that the functions and behaviors of the flight automation can be described using mission constructs like phase of flight, control modes, and targets for altitude, heading, and speed. To pilots each operational procedure is a meaningful subtask to be accomplished during a mission. Each is described by an objective or intention, a situation in the mission when it should be invoked, and the behaviors to accomplish the objective.

1.3.2 The Design Process for Operational Procedures

Operational procedures are developed using task analysis and knowledge engineering techniques. The participants in the process are senior pilots, flight test engineers responsible for commercial air transports, and avionics engineers with extensive jump-seat experience.

The design team first specifies the nature of the task and what its subtasks inputs, and outputs are. The next step in the design process is to identify and agree on an initial set of operational procedures. The dialogue was performed iteratively by asking two questions: (1) What should the automation do in this scenario? and (2) When does the automation perform a given action? Question 1 defined the behavior given in a scenario. Question 2 defined the scenario given in a behavior. This second phase generates a few hundred operational procedures for a task.

The number of operational procedures generated by the design process requires organization to facilitate understanding of the rules by pilots as well as designers. The first organizing principle is phase of the mission (e.g., preflight, taxi, takeoff, climb, cruise, descent, approach, landing, taxi). The second principle is to organize the rules into a hierarchy for each phase. In organizing the operational procedures into a hierarchy, a trade-off has to be made between the number of operational procedures at any level and the visibility of the operational procedures. Pushing a set of operational procedures down to a lower level hides their behavior. Leaving the operational procedures at the higher level extends the list of operational procedures at this level.

The critical point to realize is that operational procedures are not an arbitrary, rule-based (nested IF THEN/ELSE) implementation of a task. Individual operational procedures are meaningful to pilots' subtasks of the task during all phases of the mission. Any given task is complex, and thus the knowledge engineering process generates a large number of rules. The rules are organized into a hierarchy to enable a pilot to understand them in spite of their large number. The top-level operational procedures are the foundation for effective annunciation and effective communication.

1.3.3 A Common Model Based On Shared Intentions

The design methodology outlined in the preceding section generates a model of the automation for a given task that is shared by the pilots and engineers on the design team. Sherry and Polson (in preparation) argue that this shared model can be transmitted to other pilots with appropriate training and to the design of new forms of annunciation (feedback) based on the model. Sherry (1995) described a formal software design methodology that took as input a representation of the operational procedures developed by the design team and generates automatically the code for the various flight automation systems. Thus, the operational procedure methodology produced a common mode shared by designers, operators, and the actual system.

Billings' (1991, 1996) analyses of human-centered automation led to the conclusion that both pilots and automation must understand each other's intentions and monitor each other's performance. Operation procedures incorporate representations of the automation's intentions and the behavior used to achieve those intentions.

1.4 Models of The Automation for Flight planning, Navigation, Guidance, and Control

It is impossible to provide a detailed description of the flight planning and navigation tasks in terms of operational procedures. Although these tasks are implemented using rule-like architectures (nested if-then-elses), individual rules do not necessarily describe a subtask that would be meaningful to pilots. In this section, we sketch out designs for these tasks based on hypothetical operational procedures. The automated guidance task for the MD-11 was designed and developed employing an early version of the operational procedure design methodology.

1.5 Flight Planning

The automated flight planning task performs three functions. First, it creates and modifies the flight plan from information entered into the CDU keyboard using symbolic representation for elements of the flight plan. Rules map these symbolic entries into sequences of waypoints defined by latitude/longitude and, in some cases, altitude and/or speed constraints. Other rules make assumptions about missing flight plan elements in order to generate a flight plan that is complete enough to yield sufficiently accurate computations of expected time of arrival, fuel consumption, and other predictions. The preplanned route is typically incomplete (e.g., lacking information about the approach and landing runway).

Another set of complex rules make in-flight changes to the flight plan required by changes in weather, air traffic, and other causes. The flight planning task contains a representation of the route currently being flown, the current phase of flight, and a complete data base of routines, airports, and navigation aids. The changes input by the pilots may be incomplete, ambiguous, or incorrect.

The rules evaluate pilot inputs, reject incorrect inputs, or make the inferences necessary to generate a safe, complete flight plan. For example, the pilot cannot enter a modification that would lead to a violation of airspace regulations (e.g., flying faster than 250 kt below 10,000 ft). The rules monitor the flight planning actions of the pilots and make strong assumptions about pilot intent when resolving ambiguities or conflicts between the current flight plan and its modifications. Thus, the rules incorporate an implicit model of the pilot and interactions between the pilot and the flight planning automation.

The second function performed by the flight planning task is to make performance predictions. The flight planning task incorporates other models, including performance models for the aircraft and engines, a model of aircraft performance limitations, and a model of the atmosphere and winds along the planned route of flight. These models are used to make arrival time and fuel consumption predictions and calculate take-off thrusts, speed, and landing speed. The computations involving these models are invoked by the rules.

The third function performed by the flight planning task is to optimize fuel economy using complex, constraint algorithms. The constraints include the cleared route, weather, weight, passenger comfort, air space regulations, and aircraft performance limitations. A flight profile that minimizes fuel consumption is to climb to cruse altitude as rapidly as possible, remain at cruse speed and altitude as long as possible, and then descend as rapidly as possible to a final approach course. Unfortunately, it is usually impossible to fly this optimal profile because of traffic around origin and destination airports.

In modern cockpits, the rule for generating and modifying the flight plan are not annunciated. The complex nature of the decision-making processes during the flight planning task can generate unexpected results and automation surprises. Some interfaces to the flight planning task include a feature that alleviates this phenomena somewhat. The flight crew is able to review entries and if they are found to be correct the crew can execute them. This method avoids the possibility of instantaneously introducing an incorrect flight plan but does not illuminate the decision-making logic underlying flight plan construction.

The outputs of the flight planning task—the lateral and the vertical flight plans—are annunciated at various levels. The lateral flight plan is displayed in complete graphical form on the navigation display (ND). This information is also duplicated on the control and display unit (CDU) Flight plan pages. The vertical flight plan is not displayed graphically. A model of the flight plan can be formulated by inspection of the CDU Flight plan pages. This task is difficult for even simple flight plans.

1.5.1 Navigation

The navigation operational procedures represent the different methods used to compute aircraft position, velocities, and accelerations and combine the outputs of available sensors to generate the best estimates of these parameters. The scenarios that invoke the operational procedures are defined based on the sensor accuracy characteristics, the raw sensor data, the position of ground-based sensors (from the navigation data base), the availability of individual sensors, pilot instructions and preferences, and rules for selecting the best combination of sensors. The behaviors for each operational procedure define the algorithms for computing and smoothing the position data. These algorithms correct the noise-induced errors between sensors and biases in the resulting position data.

In modern cockpits, the operational procedures for the navigation task are annunciated clearly. The ND and the CDU navigation pages display the active combination of sensors used to compute the aircraft position. The aircraft position is also clearly annunciated on the ND and CDU Performance, Position, Flight plan, and Navigation pages.

1.5.2 Guidance

The guidance task takes as input the lateral and vertical flight plan from the flight planning task and the position of the aircraft output by the navigation task. The outputs of the guidance task are commands to the control task specifying lateral and vertical control modes with targets for the specified mode.

The guidance task includes operational procedures for flying each leg of the flight plan. Like the flight planning task, the guidance task may be decoupled into lateral guidance and vertical guidance. The operational procedures for the lateral guidance task identify the current leg in the flight plan and then select an appropriate lateral guidance operational procedure which issues a track or heading target to be flown by either a track or heading control mode.

The operational procedures for the vertical guidance task identify the current leg of the flight plan and then select an appropriate vertical guidance operational procedure to achieve the objectives of the leg. A set of ten vertical guidance operational procedures, representative of the vertical guidance operational procedures on the MD-11, are summarized in Table 1. The scenarios define all possible combinations of situations in which the aircraft may be relative to the vertical flight plan.

Table 1
Summary of Objectives and Strategies of the Vertical Guidance Operational Procedures (from Sherry and Polson, 1995, p. 14)

Operational Procedure: Objectives and Strategies
Takeoff: Airmass-referenced ascent from Runway Threshold to Acceleration Altitude
Climb: Airmass-referenced ascent from Acceleration Altitude to the Cruise Flightlevel
Climb Intermediate Level: Level flight at Clearance Altitude or Climb Altitude Constraint
Cruise: Long-range level flight at the Cruise Flightlevel
Path Descent: Earth-referenced descent on the Descent/Approach Path
Descent Intermediate Level: Level flight at Clearance Altitude or Descent Altitude Constraint
Late Descent: Airmass-referenced descent with automated speed selection and airbrake extension to return the aircraft to the Descent/Approach Path
Early Descent: Airmass-referenced descent to reacquire the Descent/Approach Path
Path Descent Overspeed: Airmass-referenced deviation from the earth-referenced path to protect the speed envelope
Airmass Descent: Airmass-referenced descent without altitude, speed, time restrictions

The operational procedures for the guidance task also monitor inputs from the pilots and make strong assumptions about the intent of pilot actions. For example, there are some situations when they will reinterpret pilot input. The crew has delegated flight planning, guidance, and control to the automation. The aircraft is at 15,000 ft climbing to a cruise altitude to 33,000 ft. The current vertical guidance operational procedure is Climb. However, ATC has only cleared the flight to 20,000 ft. The pilot as put 20,000 in the model control panel (MCP) altitude window, and the aircraft will level off under control of the Climb Intermediate Level operational procedure if the value in the altitude window is not increased before the plan reaches 20,000 ft. At 18,000 ft, ATC clears the flight to 33,000 ft. The pilot should enter 33,000 in the altitude window, but he makes an error and enters 15,000. The aircraft will immediately start to level off, but it will not descend to 15,000 ft. The automation detects the conflict between the goal of the Climb operational procedure, climb to cruise altitude, and the value entered in the altitude window and resolves the conflict by leveling off the aircraft.

In modern cockpits, the operational procedures for the guidance task are not annunciated. With deep knowledge of the scenarios and behaviors associated with the operational procedures, the objective and actions of the automated avionics systems can be inferred from the guidance targets (described below). The large, and complex nature of the decision making in the guidance task results in unexpected behavior and automation surprises.

The outputs of the guidance task, the altitude, speed, and track (heading) targets are well annunciated. These targets typically appear in altitude and speed displays (dials or tapes) and sometimes on the FMA. The track (heading) target may be displayed on the rolling compass. When these targets are manually selected they appear in the MCP windows. When these modes are generated from the automation, the MCP windows are typically dashed or display the armed targets.

What is completely missing is annunciation of the guidance task's objectives and the representations of the current and predicted situation (the operational procedures and their scenarios). Accurate information about the guidance task's objectives and current and predicted situation representation is required to understand the behavior of the avionics and to evaluate the reasonableness of a proposed maneuver. Here again, the current scenario can be constructed by scanning critical CDU pages and the ND. However, this takes time and the construction process may not be completed successfully.

1.5.3 Control

The automation for the control task is also a hybrid technology. Rules invoke the modes. The rules of the control task include the integrated pitch/thrust control modes and the heading/track lateral modes. The scenario defines the conditions for engagement and initialization of the linear control laws. The behavior describes the input/output transfer function of the closed-loop control law. There is a model for each mode implemented as linear differential equations with feedback terms (McRuer et al., 1973).

There is another set of rules that monitor pilot inputs and the performance of the aircraft. These rules implement envelope protection. For example, these functions prevent the aircraft from stalling or exceeding its maximum speed limit or from being maneuvered too violently. Envelope protection can provide feedback to pilots signaling an approaching design limit (e.g., shaking the yoke to signal an impending stall) or can veto a pilot's desire to make a violent maneuver or to command more than 100% of the maximum rated thrust in an emergency. The complexity, authority (ability of veto pilot decisions), and feedback provided by envelope protection functions are controversial topics in the literature (Sarter & Woods, 1995a).

In the modern cockpit the control-modes are annunciated specifically in the FMA portion of the primary flight display (PFD). The outputs of the control task, the pitch, roll and thrust commands, are not annunciated explicitly. The pitch and roll commands appear on the Flight Directors (if they are displayed). The commands can also be inferred from the actual pitch and roll of the aircraft displayed on the PFD which exhibits roughly a one-second delay in response to the command and by the movement of the yoke and rudder pedals (if coupled). This annunciation has proven satisfactory. Although there are new ideas about the form of the annunciation, there appears to be a consensus that the current content is satisfactory.

1.6 Pilots' Models of the Automation

Numerous researchers (e.g., Billings, 1996; Vakil, Hansman, Midkiff, & Vaneck, 1995) and pilots have pointed out that pilots are not provided with a comprehensive model of the avionics during training and that they may evolve incomplete and potentially incorrect models from their line experience. Various researchers have described operational issues and training problems that they hypothesize are caused by problems ranging from lack of necessary feedback to the pilot to discrepancies between pilots' understanding and the actual operation of the complex subsystems that make up the flight automation (Eldredge, Mangold, & Dodd, 1992; Hutchins, 1993; Sarter & Woods, 1992, 1994; 1995a,b; Wiener, 1988, 1989; Vakil, Hansman, Midkiff, & Vaneck, 1995). Mangold and Eldredge (1995) concluded that a significant portion of the automation is not effectively used by pilots, that pilots may be unfamiliar with some of the functionality of the avionics, and that limitations in feedback on the state of the avionics and the state of the flight plan result in some uncertainty on the part of flight crews.

Pilots' models of flight automation are complex and interact with their knowledge and skills of how to fly the aircraft. Pilots delegate tasks to the automation that they can perform themselves. Successful delegation involves programming the fight automation to properly perform the delegated task and understanding how the automation is going to fly the aircraft when it is given the authority to perform the task (Billings, 1996).

2. Conclusions and Suggestions for Further Research

The Cockpit System Framework provides a novel analysis of operational issues and training problems described in the current literature. This section summarize the conclusions and proposals for further research.

2.1 Current Annunciation Schemes

Sherry and Polson (1995) concluded that the primary interfaces to the automation (FMA and MCP) in current glass cockpit aircraft use annunciation schemes that are generalizations of designs developed for an earlier generation of avionics systems that only automated the control task (an interface to the autopilot). Pilots must utilize effortful, cognitive processes to construct useful representations of the current state of the avionics, scanning other displays in addition to the FMA. The information on various displays must be integrated to make useful inferences about the immediate and near term behavior of the aircraft.

Sherry and Polson (1995) hypothesize that many of the operational issues with modern avionics are caused by lack of annunciation and training on the guidance task. The guidance task is hidden in current annunciation schemes. Problems attributed to the complexity of the mode structure (e.g., Billings, 1996; Hutchins, 1993; Sarter and Woods, 1995a) may be caused by interactions between the guidance and control tasks.

2.2 Annunciation Based on The Cockpit System Model

Sherry and Polson (1995) propose that annunciation in the cockpit should provide the flight crew with the automation/manual configuration of each of the four tasks and that annunciation for flight planning, guidance, and navigation should be based on operational procedures. In particular, a new annunciation scheme should distinguish been guidance and control tasks. Guidance and control actions have different implication for the behavior of the aircraft. The control mode and current targets determine the immediate behavior of the aircraft. Guidance task actions determine the behavior of the aircraft for the next several or tens of minutes. Pilots need both kinds of information. The proposed McCrobie and Sherry (1996) experiment is a preliminary test of this hypothesis.

2.3 Further Research

Sherry and Polson (1995) made numerous claims about the superiority of the Cockpit System Framework as a basis for the design of flight automation. Unfortunately, there is no research that enables us to directly support such claims. This section briefly summarizes an ongoing research program that will provide direct evidence for the Cockpit System Framework.

Sherry and Polson (in preparation) review the literature on operational issues and training problems. They are mapping the findings and conclusions of other investigators into the Cockpit System Framework. The goal of these re-analyses is to obtain evidence for claims—like many automation surprises are caused by not annunciating the guidance task in current cockpits.

McCrobie and Sherry (1996) have proposed an experiment in which pilots are taught the operational procedure model of the guidance task and must use the model to predict the future behavior of an aircraft. This experiment will compare performance on the prediction task using two different interfaces to the avionics. The first is the typical mode control panel interface found in glass cockpits; the second is a novel annunciation scheme proposed by Sherry and Polson (1995).

Simulation models of pilots performing the prediction task will be constructed based on Kitajima and Polson's (submitted) model of instruction following for the two interfaces. Comparisons will be made between pilot behavior on the experimental task and the simulation results. These theoretical and empirical results will be employed to develop a new design evaluation method for avionics interfaces. The method is similar to the Cognitive Walkthrough (Wharton, Rieman, Lewis, & Polson, 1994), a method for evaluating usability of office automation applications.

The development processes for modern airliners make extensive use of theory-based methods to evaluate alternative designs. A small number of promising alternatives can be selected for further evaluation by testing working prototypes. Development of the Boeing 777 shows that such methods can dramatically reduce costs while leading to a superior product.

The flight deck is one area where such theory-based techniques have not been utilized to develop new designs. In fact, the flight deck of the Boeing 777 is similar to that of the Boeing 747-400 and 757/767. Industry appears unwilling to explore alternatives to the current automated flight decks whose basic design is almost 15 years old. Current methods for evaluating flight deck designs require the use of working prototypes. This process is slow and costly. Theory-based design evaluation methods would enable exploration of a range of alternatives to find new designs that could significantly reduce training costs and lead to better crew performance.

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